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Energy-Efficient Rate Adaptation MAC Protocol for Ad Hoc Wireless Networks[1]

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Abstract

Resource constraints in ad hoc wireless networks require that they are energy efficient during both transmission and rate adaptation. In this paper, we propose a novel energy-efficient rate adaptation protocol that selects modulation schemes online to maximize throughput based on channel state while saving energy. This protocol uses the Distributed Power Control (DPC) algorithm [1] to accurately determine the necessary transmission power and to reduce the energy consumption. Additionally, the transmission rate is altered using energy efficiency as a constraint to meet the required throughput, which is estimated with queue fill ratio. Moreover, back-off scheme is incorporated to prevent energy wastage and to avoid retransmissions in the event of congestion. The back-off scheme employs backpressure mechanism to emulate congestion control. Consequently, the nodes will conserve energy when the traffic is low, offer higher throughput when needed and save energy during congestion by limiting transmission.

1. Introduction

Due to the need for higher throughputs in the next generation wireless networks, modulation schemes that render higher data rates have been introduced; for example 54 Mbps capability of the 802.11g standard. However, the communication range decreases as the rate increases. Hence, connectivity is reduced for modulation schemes that provide higher throughput. A simple remedy is to increase the transmission power. However, the node's energy is drained quicker. Moreover, the energy-efficiency of transmission, which is measured as the number of bits transmitted per joule, decreases with rate. Consequently, the energy consumption of the wireless nodes increases with higher data rates thus reducing the life-time of the nodes and the network.

A more appropriate solution involves using several modulation schemes and dynamically selecting a suitable one online based on the channel state and the network traffic. The basic concept was analyzed in [4] and proved to be very effective. Relevant parameters for the selection of the modulation scheme include bit-error-rate (BER) and signal to noise ratio (SNR). The former indicates the probability of error occurrence during a transmission for a given SNR. The latter defines the received signal quality. Hence, for a given modulation scheme, a threshold SNR can be calculated according to a desired BER level. In general, for small target BER (less errors) a high SNR is typically required.

To address the rate adaptation in wireless networks based on 802.11 standard, several schemes were proposed in the literature [2][3]. However, these protocols focus mainly on maximizing the throughput, regardless of transmission power, channel state and network congestion. For instance, the Auto Rate Fallback (ARF) [3] protocol incrementally alters the transmission rate after experiencing a number of consecutive correct or erroneous packet receptions. For this reason, ARF slowly converges to the more appropriate rate. Consequently, significant number of packets is dropped due to low SNR or sent at low transmission rate thus reducing the throughput. By contrast, the Receiver Based AutoRate (RBAR) protocol proposed in [2] uses the predefined lower and upper SNR thresholds to select an appropriate modulation scheme. By using the measured SNR value from the previous MAC frame, a more suitable modulation scheme is selected using SNR thresholds. However, the channel measurements used to select a given rate are from the previous transmission, and do not accurately describe the channel state for the subsequent transmission. Moreover, the data is sent at the maximum power in both ARF and RBAR. Hence, the protocols are not energy efficient.

The proposed rate adaptation protocol uses the distributed power control (DPC) scheme from [1] to predict the channel state and to meet the target SNR. Thus, the proposed scheme can more appropriately selects the rate over available protocols. Additionally, the proposed scheme selects a wide range of suitable rates by taking into account the demanded throughput and the energy efficiency, to accommodate the network congestion and to conserve energy.

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It is important to note that the throughput and energy-efficiency are affected during congestion and this issue is ignored by existing protocols [2][3]. By contrast, the proposed protocol uses the back-off mechanism to mitigate the impact of congestion. As a result, the packet forwarding is prevented if the next-hop node cannot buffer them or the channel state is not conducive. Consequently, the maximum possible rate will be selected in the case of high congestion to free the channel quicker. Hence, the proposed protocol maximizes throughput and saves energy by selecting appropriate rate while minimizing the packet losses in the case of congestion. Additionally, the proposed scheme modifies the transmission power to save energy during the rate adaptation, while the other protocols always use the maximum transmission power.

First, we discuss the overview of the proposed rate adaptation scheme followed by its detailed description. Next, the back-off mechanism is explained. Then modifications to the MAC protocol are listed. Finally, the simulation results and conclusions are presented.

2.Rate Adaptation

A given communication application requires that the BER value is below a certain level. For wireless networks, the BER translates into a minimum SNR for which the packet is considered as successfully decoded. The relation between the BER and the SNR threshold is well defined for a given modulation scheme [2]. In general, a SNR threshold increases with the rate. Consequently, the minimal required transmission power has to be increased with the rate. On the other hand, the power value is limited by the hardware capabilities. Thus, there is a maximum SNR value and corresponding modulation that could be achieved if the maximum power is used. Given the maximum power, the maximum rate will result in highest throughput but lowest energy consumption. Channel state impacts the rate.

2.1.Overview of the proposed scheme

The proposed protocol uses the DPC algorithm presented in [1] to predict the channel state one step ahead, which is subsequently used to select the rate and calculate the transmission power. Additionally the rate is altered depending upon its energy-efficiency and local queue utilization. In consequence, a more accurate rate is selected while transmitting the DATA frame when compared to ARF or RBAR. Additionally, the power control reduces energy consumption by selecting only the minimal required power based on the channel state.

Fig. 1 presents the dataflow for the proposed rate adaptation scheme. First, the SNR thresholds are pre-defined for all modulation schemes in accordance with the desired BER value thus reducing the computation overhead. During communication, the DPC algorithm is used to continuously assess the channel state and to calculate the transmission power for the target SNR_0 of the lowest supported rate. Then, the maximum and minimum rates for the channel state are estimated by taking into account the energy-efficiency. Next, a suitable rate is selected between the minimum and the maximum rate by using the queue utilization. Finally, a more suitable transmission power for the selected rate is determined.

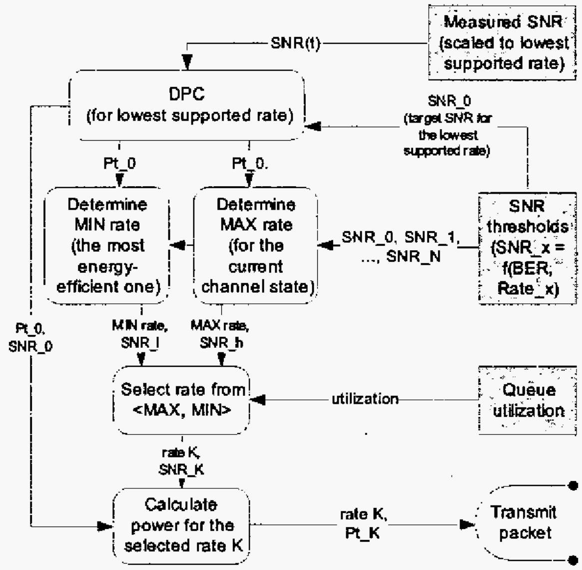

Fig. 1. Dataflow of the proposed rate adaptation scheme.

Remark: In this paper we assume that all nodes are capable of handling the same set of N modulations. In case of the heterogeneous network, the nodes will have to exchange the rate information by using the control packets. Also, to simplify the description of the problem the modulation schemes are sorted by rate.

3.Rate Adaptation Using DPC

The details of the rate adaptation scheme are presented in the following subsections. First, we briefly introduce the DPC protocol used in the proposed rate adaptation scheme. Subsequently, we present the estimation of the maximum rate that can be used. Next, the determination of the most energy-efficient rate is explained. Then, the rate selection according to the queue utilization is presented. Finally, the power calculation for the selected rate is derived.

3.1.Distributed Power Control

The goal of the transmitter power control is to maintain a target SNR threshold for each network link while the transmitter power is adjusted autonomously by each link so that the least possible power is consumed in the presence of channel uncertainties. Therefore, the decision-making is fully distributed at the link level with minimal overhead compared with its counterpart for centralized operations. The DPC algorithm used in this paper is capable of predicting changes in the channel state. Moreover, the analytical convergence of the algorithm is proven mathematically in [1].

A feedback loop is used between the transmitter and the receiver in order to successfully implement the DPC algorithm. The detailed description of the implementation can be found in [1].

3.2.Estimation of channel conditions

The proposed protocol uses a threshold method similar to the case of [2] to determine the maximum rate possible for the given SNR. The maximum SNR that corresponds to the maximum transmission power is also to be determined. In this paper, the DPC feedback is used to predict this maximum SNR for transmitting the next frame.

Theorem 1: (Maximum SNR prediction): Given the maximum transmission power defined for the network, and DPC feedback information [1] for the lowest supported rate, the maximum possible SNR for subsequent transmission can be predicted using

$$SNR_{MAX}(t) = SNR_0 * Pt_{MAX} / Pt_0(t) \tag{1}$$

where $SNR0$ is the target SNR for the lowest supported rate, $Pt0\ (t)$ is the estimated power value for the lowest supported rate, and $PtMAX$ is the maximum transmission power defined for the network.

Proof: First, let us consider the SNR ratio of a received signal expressed as

$$SNR(t) = Pr(t) / I(t) = Pt(t) * Gi(t) / I(t) \tag{2}$$

where $Pr(t)$ is a received signal strength, $Pt(t)$ is the transmission power, $Gi(t)$ is a gain (loss) experienced by the signal, and $I(t)$ is a interference plus noise level.

It is important to note that SNR depends upon transmitted power. Furthermore, we can calculate the ratio of two SNR values using the corresponding transmission power values. This ratio is equal to

$$\frac{SNR_l(t)}{SNR_k(t)} = \frac{Pt_l(t) * Gi(t) / I(t)}{Pt_k(t) * Gi(t) / I(t)} = \frac{Pt_l(t)}{Pt_k(t)} \tag{3}$$

where $SNRl(t)$ and $SNRk(t)$ are the measured signal-to-noise ratio, and $Ptl(t)$ and $Ptk(t)$ are the corresponding transmission powers used in each case respectively.

Let the value of $Pto(t)$ needed to meet the target SNR_O along with the maximum power PtMAX is known. The maximum SNR, when the maximum power is used, can be calculated from equation (3) as

$$SNR_0 / SNR_{MAX}(t) = Pt_0(t) / Pt_{MAX} \tag{4}$$

Equation (4) can be rewritten as (1).

3.3. Calculation of maximum usable rate

Next, the maximum achievable rate is selected using threshold method similar to the case of RBAR protocol [2]. However, in the proposed scheme, the current SNR value is an estimation of the SNR for the next transmission, while in the case of RBAR, the SNR is out-dated value measured from the previous frame reception (that is half loop-delay before the DATA frame). Hence, the proposed protocol will be able to accurately select the rate taking into account the channel state. The highest rate ***m*** is selected from

$$SNR_m < SNR_{MAX}(t) < SNR_{m+1} \tag{5}$$

where $SNR_{MAX}(t)$ is the estimated SNR ratio if the maximum power would be used for transmission, and $SNRm$ is the lower threshold for m-th rate. All modulation schemes that render rates up to m-th rate are considered usable since the transmission power, for these rates, is below the maximum network threshold.

3.4. Calculation of the minimum usable rate

The most energy-efficient rate will become the minimal rate that can be used. Under the ideal circumstances, energy efficiency decreases with an increase in rate. Hence, the lowest rate should be the most energy-efficient. However, in the proposed protocol, the train of pulses is used to overcome the hidden terminal problem [1]. These pulses introduce the energy overhead, which becomes an additional factor to be considered for rate adaptation. Hence, lowest rate is not always energy efficient. Consequently, the most energy-efficient rate is found by comparing the energy consumed at each rate for the given packet under the current channel state. The rate with lowest energy consumption will be selected as minimum usable rate.

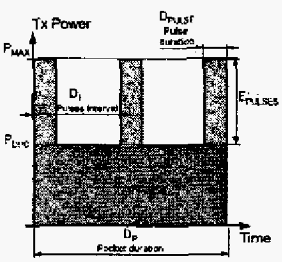

Fig. 2. Energy consumption during packet transmission.

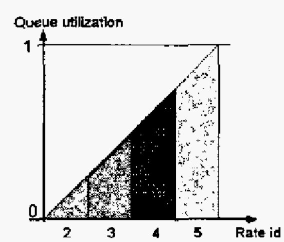

Fig. 3. Rate selection as a function of queue utilization.

Normally, the energy consumed for transmission is equal

$$E = D * Pt = Pt * Pkt\_size / R \tag{6}$$

where E is the energy consumed, D is the duration of transmission, R is the current rate, and Pt is the current transmission power. For the case of power selected by DPC algorithm with the train of pulses, the energy consumed during transmission is equal to

$$E_{TOTAL} = E_{DPC} + E_{PULSES} \tag{7}$$

where E_{TOTAL} is the total energy consumed on transmission of the packet with pulses, E_{DPC} represent the energy consumed for the transmission of the packet using power selected by the DPC algorithm, and E_{PULSES} denotes the additional energy consumed for the generation of pulses. Fig. 2 illustrates such a packet transmission.

Therefore, E_{DPC} and E_{PULSES} can be expressed using (6) as

$$E_{DPC} = Pt_{DPC} * Pkt\_size / R \quad (8)$$

and

$$E_{PULSES} = (Pkt\_size / R) * (D_{PULSE} / D_I) * (Pt_{MAX} - Pt_{DPC}) \quad (9)$$

After substituting (8) and (9) into equation (7) to get

$$\begin{aligned} E_{TOTAL} &= (Pkt\_size / R) * Pt_{DPC} \\ &+ (Pkt\_size / R) * (D_{PULSE} / D_I) * (Pt_{MAX} - Pt_{DPC}) \end{aligned} \quad (10)$$

It is important to note that for the given packet size and rate, the total energy is linearly dependent upon the DPC power. Also the DPC power for a given rate increases proportionally to the target SNR as per equation (3). Thus for a rate ***k***, equation (10) is expressed as

$$\begin{aligned} E_{TOTAL,k} &= (Pkt\_size / R_k) * (D_{PULSE} / D_I) * Pt_{MAX} \\ &+ (Pkt\_size / R_k) * (SNR_k / SNR_0) * (1 - (D_{PULSE} / D_I) Pt_0(t) \end{aligned} \quad (11)$$

The upper and lower thresholds of the DPC power (calculated for the lowest supported rate) need to be found so that the most energy-efficient rate can be selected. By equating (11) for the two successive rates, the threshold values for the rate adaptation are determined as

$$E_{TOTAL,k} = E_{TOTAL,k+1} \quad (12)$$

Using (11), the rate's upper threshold of power is give by

$$Pt_{o,k} = \frac{\varphi}{1-\varphi} * \frac{1-\alpha_k}{\gamma_k - \alpha_k * \gamma_{k+1}} * Pt_{MAX} \quad (13)$$

where $\alpha_k = R_k / R_{k+1}, \gamma_k = SNR_k / SNR_0$ and $\varphi = D_{PULSES} / D_I$.

Table 1: Power thresholds for selecting the most energy-efficient rate

SNR [dB]	SNR	Rate [Mbps]	Upper thresholds of Tx power [mW]
10	10.00	1	> 20.09
14	25.12	2	20.09
22	158.49	4	10.64
28	630.96	6	1.49
32	1584.89	8	0.30

It is important to note that the threshold value depends upon the transmission power selected by the DPC algorithm for the lowest supported rate. Hence, the power thresholds can be calculated in advance, reducing calculation overhead of the protocol. Table 1 presents the thresholds for a set of five rates used in the simulations. For example, if the transmission power calculated by the DPC algorithm is equal to 10mW, then the 2Mbps is the optimal rate since 10mW is less then 20.09mW (2Mb).

3.5. Selecting a modulation scheme to overcome congestion

In the previous subsections, the maximum (highest throughput) and energy-efficient rates have been calculated. The throughput increases with the rate; however, the lower the rate used, the more bits can be transmitted per joule. Therefore, the rate selection has to deal with tradeoffs between throughput and energy-efficiency. Hence, the selection of a modulation scheme that results in the best throughput while satisfying the energy constraint is discussed next. In the proposed protocol, the local queue utilization at the transmitter is used as an indication of the required throughput, and will impact the rate selection method.

Since high traffic rate implies high buffer occupancy, the rate should be selected based on the local buffer occupancy at each node. The basic idea is presented in Fig. 3. The lowest supported rate is selected when the queue at the transmitting node is empty. Increasing queue utilization at this node indicates a higher traffic demand. Hence, the higher rate or the modulation scheme that result in higher rate is selected.

In other words, the lowest supported rate will be chosen if the congestion is low. As the congestion in the network increases, the queue utilization will increase. Consequently, a higher rate will be selected rendering a higher throughput. As the congestion decreases, the lower rate will be selected resulting in higher energy efficiency.

3.6. Power calculation for the selected rate

The DPC algorithm calculates the transmission power only for the lowest supported rate. In the case of proposed rate adaptation scheme, the necessary power has to be selected to reflect the used rate. Hence, an appropriate transmission power for a given rate is calculated as follows.

Theorem 2 (Power Control with Rate Adaptation): Given the lower and upper threshold values of SNR for a given rate, and the DPC feedback information for the lowest supported rate, the transmission power for the proposed scheme is given by

$$Pt_k(t) = Pt_0(t) * SNR_k / SNR_0 \quad (14)$$

where *SNR0* is the target SNR for the lowest supported rate, *SNRk* is the target SNR for the k-th modulation scheme, *Pt0 (t)* is the estimated power value for the lowest supported rate, and *Ptk (t)* is the power value for the k-th modulation scheme. Moreover the error in estimation of power is bounded.

Proof: Recall the ratio of SNR values depending on transmission power selected is expressed as in (3). Let's assume that we know the value of *Pto(t)* , which is needed to meet the target *SNRo* (corresponding to the lowest supported rate). Let the target *SNRk* for a different rate is known. The transmission power *Ptk(t)* needed to meet the target *SNRk* can be obtained from equation (3) as

$$SNR_0 / SNR_k = Pt_0(t) / Pt_k(t) \quad (15)$$

Equation (15), after rewriting, becomes (14). Error in estimation for the k-th rate is bounded provided the power calculated by DPC is bounded. Because the power for the lowest supported rate is estimated using the DPC algorithm, the power for the k-th rate is also an estimate. Assume that ε_0 is the maximum error in estimation of power by DPC algorithm. Applying this to equation (14), the maximum error in estimation for the k-th rate ε_k is given as

$$\varepsilon_k = \varepsilon_0 \, SNR_k / SNR_0 \tag{16}$$

It is important to note that the error in estimation for the k-th rate is proportional to the error in estimation of the basic rate and the ratio of the two SNR values. Consequently, the proposed DPC protocol can be used to calculate transmission power while noting that the error in estimation is bounded.

4. Back-off mechanism

The desired back-off mechanism should dictate the back-off interval. Higher queue utilization in the next hop node indicates that a longer back-off interval is needed for all the nodes in the region so that the next hop node will access the channel more often. A quadratic relationship for backing off is considered in this algorithm, with the intention that for high buffer occupancy the back-off will be high preventing buffer overflowing, and that for low buffer occupancy the delay caused by back-off will be low thus not undermining throughput. The back-off interval is calculated using

$$BI = \rho * SF * \left(1 + \alpha * Q_{NEIGHBOR}(t)^2\right) \tag{17}$$

where BI is the back-off interval, ρ is the random number, SF and α are the scaling factors, and $Q_{NEIGHBOR}(t)$ is the utilization of queues at the next-hop node.

5. Proposed MAC protocol

The DPC protocol presented in [1] between a transmitting and receiving node is modified to accommodate the rate adaptation. The DPC power feedback is added to the MAC frames similar to [1]. To implement the rate-adaptation, the MAC protocol has to be incorporated with the rate selection algorithm along with the necessary transformation required for the power and SNR values shown in (14) and (18). Additionally, the MAC frames have to be modified to include the queue utilization for the proposed back-off mechanism.

The RTS, CTS, ACK frames are transmitted using the lowest supported rate while the DATA frames are transmitted at the rate selected by the algorithm. The header of an 802.11 frame contains a standard field which indicates the rate used for payload transmission. We use this field to indicate the rate of transmission in order to inform the receiver such that it can correctly decode the payload.

The DPC requires that the input value of SNR correspond to the transmission power calculated by the DPC algorithm. However, in the proposed scheme, the power value is modified according to equation (14). Hence, the received SNR will be invalid for the DPC algorithm. In such a case, the measured $SIR_k(t)$ needs to be scaled to correspond to the lowest supported rate. Multiplying both sides of eqn. (15) by $G_i(t)/I(t)$ we get

$$SIR_0(t) = SIR_k(t) * SNR_0 / SNR_k \tag{18}$$

where SIR_0 and SIR_k are target values for the lowest supported rate and k-th rate respectively, $SIR_k(t)$ is measured SNR ratio, and $SIR_0(t)$ is the SNR value that would be measured if the lowest supported rate (and adequate power) was used. Now, the $SIR_0(t)$ value can be used in the DPC algorithm to calculate the transmission power for the lowest supported rate.

6.Simulations

The NS-2 simulator was used for evaluating the proposed rate adaptation protocol. The one-hop, two-hop and random topology are used to evaluate the proposed protocol. However, due to the analytical nature of the technique, any network topology can be utilized. The one-hop topology is used to evaluate performance of the protocols in the presence channel fading. The two-hop topology, sets up two flows that are routed through a relay node, which becomes a bottleneck for communication. The last topology uses 50 nodes randomly located in the area of 1000x1000m with 25 flows set up through the network. The proposed protocol is compared with the RBAR [2].

The standard AODV routing protocol was used whereas any routing protocol can be employed with the rate adaptation scheme since the proposed work is independent of a routing protocol. The following values were used for all the simulations: 5 modulation schemes were used with data rates equal to 1, 2, 4, 6 and 8 Mbps, and the target SNR values of 10, 14, 22, 28, 34 dB respectively. The maximum power used for transmission is selected as 0.2818 W. For the proposed DPC, the design parameters are selected as Kv=0.01, σ = 0.01. The safety margin in the case of retransmissions is set to 1.5 for the proposed DPC scheme. The NS-2 was modified to calculate SNR value, and to implement the fading channel with path loss, shadowing and Rayleigh fading loadable from a sample file, as it was done in [1]. Each node starts using fading data from different time-shift in the sample file, at the same time the repetitiveness of the fading between simulations is guaranteed.

6.1. One-hop results

Table 2 presents the average throughput achieved by the protocols with flow rates of 0.5Mbps, 2Mbps and 4Mbps. Table 3 presents the energy efficiency of both protocols for different rates. Both protocols can transmit with similar throughput. However, the efficiency of the

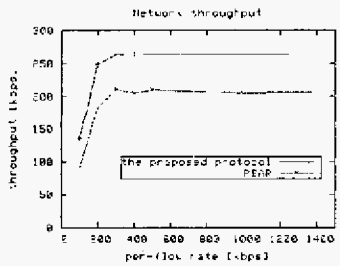

Fig. 4 Throughput for varying per-flow rate

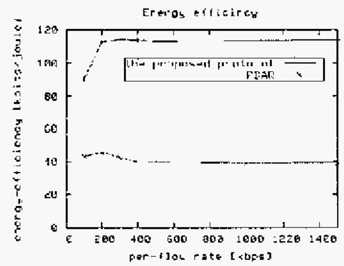

Fig. 5. Energy efficiency for varying per-flow rate.

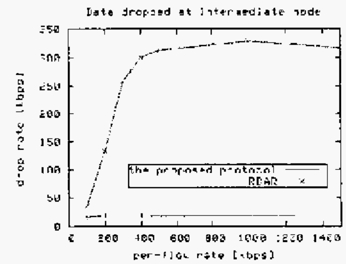

Fig. 6. Drop rate for varying per-flow rate.

proposed protocol outperforms the RBAR, such that the proposed protocol can transmit 3.5 times more data for the same energy consumed. The energy efficiency is the result of energy efficient rate adaptation.

Table 2: Throughput [kbps]

Protocol	0.5 Mbps	1.2 Mbps	4 Mbps
RBAR	499	1083	1424
The proposed protocol	499	1082	1434

Table 3: Energy efficiency as data transmitted per joule [kbits/joule]

Protocol	0.5 Mbps	1.2 Mbps	4 Mbps
RBAR	196.73	217.77	233.65
The proposed protocol	670.58	780.05	803.58

6.2.Two-hop topology results

Fig. 4 illustrates the total throughput achieved for this network with varying per-flow rates. The proposed protocol outperforms the RBAR for all the traffic rates since it intelligently selects the rate based on channel state and congestion. Moreover, when observing energy-efficiency in Fig. 5, the proposed protocol can transmit up to three times more data for the same amount of energy consumed due to the inclusion of DPC. Fig. 6 presents the drop rate at the intermediate node. The number of dropped packets increases for RBAR as traffic increases, while for the proposed protocol this rate is constantly low because, in the proposed rate adaptation scheme, the buffer occupancy of the receiving node is fed back to the transmitter. This information is used at the transmitting node to delay transmissions thus preventing packet drops and retransmissions, whereas other protocols transmit constantly dropping packets at the relay node. This improvement, which is an effect of using back-off mechanism, adds up to energy-efficient transmission as observed in one-hop topology (though we cannot compare them directly due to differences in topology) giving higher throughput when compared to the RBAR.

6.3.Random topology result with 50 nodes

Fig. 7 shows the total data transmitted by 25 constant bit-rate (CBR) sources and that is received at the destinations in the presence of fading channels. The energy efficiency is presented in Fig. 8. The proposed protocol transmits more data and consumes less energy per bit when compared to RBAR protocol for all the traffic rates due to the proposed rate adaptation. These results confirm conclusions from the previous simulations.

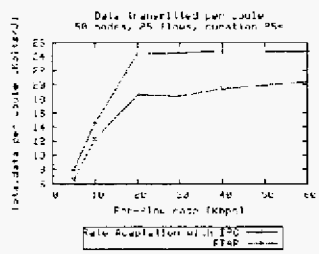

Fig. 7. Data transmitted per joule for varying per flow-rate.

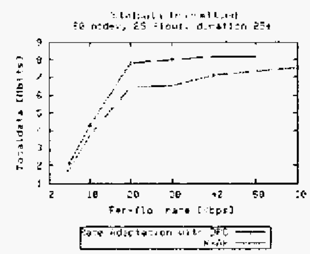

Fig. 8. Total data transmitted for varying per flow-rate.

7. Conclusions

A novel energy efficient rate adaptation protocol is introduced that adaptively selects the rate based on DPC, channel rate and queue utilization. The selection of the rate is performed online by taking into account the congestion, throughput required and buffer occupancy. The back-off intervals are altered based on congestion. Simulations confirm that the data can be transmitted faster with fewer dropped packets while consuming less energy. Thus, the network life time is extended and quality of service improved.

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